Automation of a Center Pivot Using the Temperature-Time-Threshold Method of Irrigation Scheduling

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Abstract: A center pivot was completely automated using the temperature-time-threshold method of irrigation scheduling. An array of infrared thermometers was mounted on the center pivot, and these were used to remotely determine the crop leaf temperature as an indicator of crop water stress. We describe methods used to automatically collect and analyze the canopy temperature data and control the moving irrigation system based on the data analysis. Automatic irrigation treatments were compared with manually scheduled irrigation treatments under the same center pivot during the growing seasons of 2004 and 2005. Manual irrigations were scheduled on a weekly basis using the neutron probe to determine the profile water content and the amount of water needed to replenish the profile to field capacity. In both years, there was no significant difference between manual and automatic treatments in soybean water use efficiency or irrigation water use efficiency. The automatic irrigation system has the potential to simplify management, while maintaining the yields of intensely managed irrigation.

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Introduction

An automated irrigation scheduling and control system that responds to stress indicators from the crop itself has the potential to lower crop management and labor requirements, and to increase yields per unit of irrigation water (Evett et al. 2000). Burke (1993) and Burke and Oliver (1993) showed that plant enzymes operate most efficiently in a narrow temperature range termed the thermal kinetic window. Wanjura et al. (1992, 1995) demonstrated that the use of this window as a canopy temperature threshold could be used as a criterion for simplifying and automating irrigation scheduling. Upchurch et al. received U.S. Patent No. 5,539,637 in 1996 for an irrigation management system based on this optimal leaf temperature for enzyme activity and a climate dependent time threshold. This was termed the temperature-time-threshold (TTT) method of irrigation scheduling. With this method, for every minute that the canopy temperature exceeds the threshold temperature, 1 min is added to the daily total (Fig. 1). If this daily total exceeds the time threshold at the end of the day, then an irrigation of a fixed depth is scheduled. Since humidity can limit evaporative cooling, minutes are not accrued if the wet bulb temperature is greater than the threshold temperature minus 2°C. Evett et al. (1996, 2000) demonstrated in drip irrigated plots near Bushland, Texas that automatic irrigation using the TTT method was more responsive to plant stress and showed the potential to outyield manual irrigation scheduling based on a 100% replenishment of crop water use as determined by neutron probe soil water content measurements.

The TTT irrigation scheduling method is easily automated with solid set systems such as drip irrigation where canopy temperatures can be measured in stationary positions in the field throughout the day. However, infrared radiation sensors mounted on self-propelled center pivots or linear move irrigation systems can provide only one-time-of-day canopy temperature measurements at each field location, and these measurements occur at uncertain times of day. The application of the TTT system of irrigation scheduling to specific locations under a center pivot or linear move irrigation system requires a method of determining diurnal canopy temperature dynamics at each location from these one-time-of-day canopy temperature measurements. It also requires a method of automatically collecting and analyzing the canopy temperature data and controlling the moving irrigation system based on the data analysis.

The objectives of this study were to: (1) apply the TTT method of irrigation scheduling to a center pivot irrigation system with an array of infrared thermocouples mounted on the center pivot itself; (2) configure the center pivot to be automatically controlled according to the plant water needs as determined from the TTT method of irrigation scheduling; and (3) compare the automatic irrigation scheduling to manual irrigation scheduling based on neutron probe soil water content measurements in the same field.

Diurnal Canopy Temperature Determination

Extrapolating a diurnal canopy temperature curve from a one-time-of-day measurement requires an estimation of the canopy temperature dynamics due to changing environmental conditions. Several different models exist that can predict the dynamics of the crop canopy temperature as part of a soil-plant-atmosphere energy

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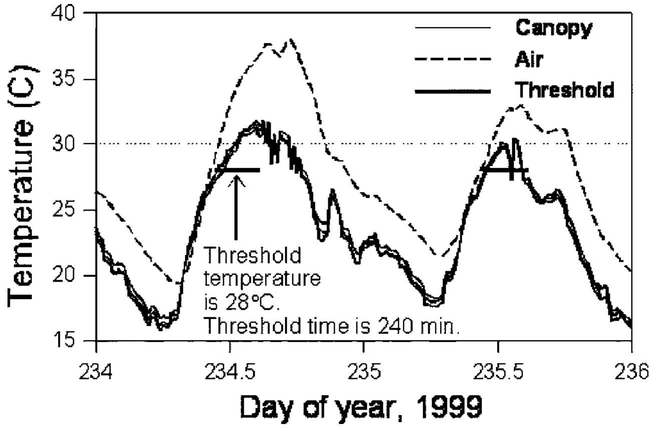

Fig. 1. Canopy temperatures of three replicate plots on corn in 1999 (Evett et al. 2000) compared with air temperature. Shown also are horizontal bars drawn at the threshold temperature of 28°C and over the length of the threshold time (240 min). Because the canopy was above the threshold temperature for more than the threshold time on day 234, irrigation occurred in the evening of that day, but not in the evening of day 235.

balance (Evett and Lascano 1993). However, these models require as input, detailed weather data, as well as knowledge of soil- and plant-specific parameters that are neither readily available nor easy to measure. The most direct and simple way to determine how changing environmental conditions over a day affect canopy temperature dynamics is to measure canopy temperature in one stationary reference location. Canopy temperatures in other parts of a field, which may be under different stresses, may be modeled relative to this reference using one-time-of-day temperature measurements from those locations (Peters and Evett, 2004a,b). If predawn canopy temperatures throughout the field (T_e; e for early) are assumed to be the same, then

$$T_{\mathrm{rmt}} = T_e + \frac{(T_{\mathrm{rmt},t} - T_e)(T_{\mathrm{ref}} - T_e)}{T_{\mathrm{ref},t} - T_e} \tag{1}$$

where T_{rmt}(°C)=calculated canopy temperature at the remote location; T_{ref}(°C)=canopy temperature from the reference location at the same time interval as T_{rmt}(°C); $T_{\mathrm{rmt},t}$(°C)=one-time-of-day canopy temperature measurement at the remote location at any daylight time t; and $T_{\mathrm{ref},t}$(°C)=measured reference temperature from the time t that the remote temperature measurement was taken.

Materials and Methods

The experimental site was a three-tower, 127 m long research center pivot located at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas (35° 11′ N, 102° 06′ W, 1,170 m elev. above MSL). The towers are located at the radial distances of 33.8, 73.3, and 112.8 m. Data were collected during 2004 and 2005 on soybeans grown on a Pullman fine, mixed, superactive, thermic Torrertic Paleustoll. Only half of the field was used to allow the other half's soil water content differences from the previous year to be evened up with a cover crop. Alternate halves were used in 2004 and 2005. Soybeans were planted in concentric circles out from the center point (Fig. 2). Four different water level treatments 12.2 m (40 ft) wide were applied radially out from the center point (100, 66, and 33% of projected irrigation needs, and a dry land, or no irrigation treatment). Each drop was pressure regulated to 6 psi. The irrigation level was controlled by nozzle sizes as appropriate. Drops were spaced every other row (1.52 m) and irrigated with low energy precision application (LEPA) drag socks. The flow rate from each drop was evaluated using a large bucket, a scale, and a stop watch and the system performance was found to adequately match the design requirements. The furrows were dammed/diked to limit water movement in the furrows. Radially, two replications of each of the irrigation level treatments were applied in a randomized block pattern with the second tower wheel track serving

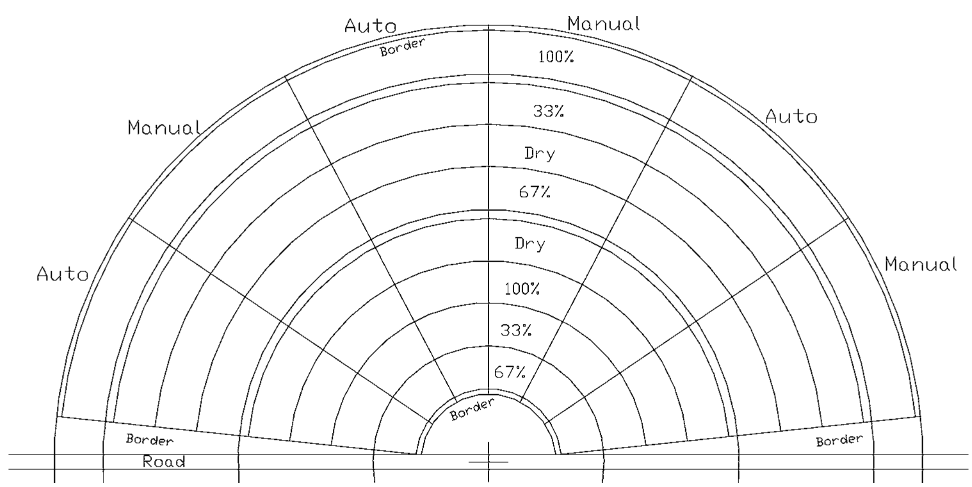

Fig. 2. Automatic center pivot irrigation experiment plot plan divided into six "pie slices." Pie slices labeled Auto were automatically irrigated, while those labeled Manual were manually irrigated. Irrigation amounts were 100% of the amount determined by each of the two irrigation scheduling methods used in the arcs labeled 100%, and in the arcs labeled 67% and 33%, the irrigation amounts were 67% and 33% of the amount applied in 100% arcs.

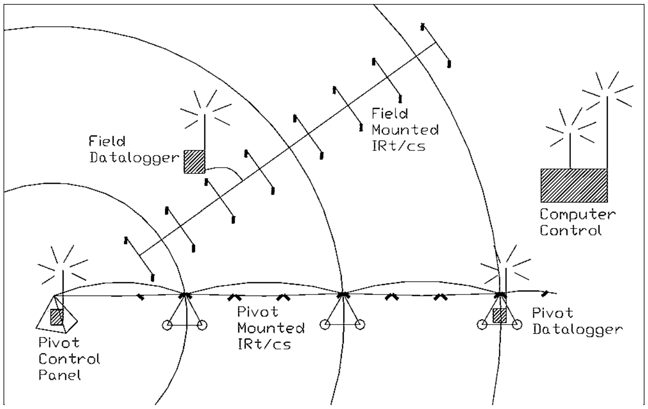

Fig. 3. Automatic center pivot control setup

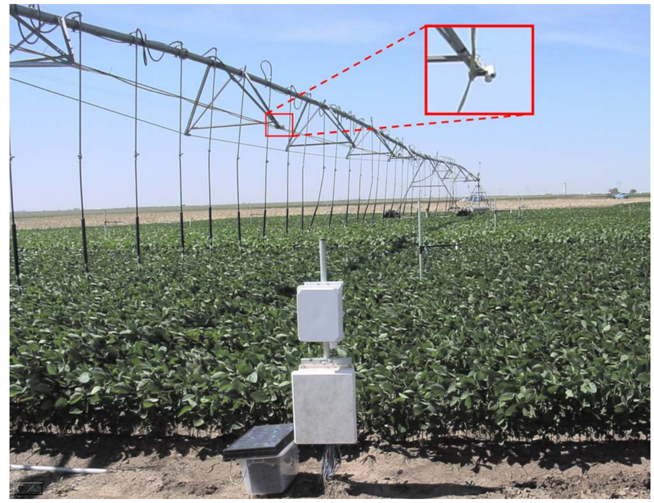

Fig. 4. Photo of the center pivot showing the infrared thermocouples (IRTCs) mounted on the pivot trusses, the field IRTCs, and the field datalogging equipment

as the block separation line. The innermost plot was not used. Along the arc of the irrigated half circle, there were three replications each of an automatically controlled (via the TTT method) treatment, and a treatment that was manually scheduled (using soil water deficiency as determined by neutron probe soil moisture content readings). These treatments were applied alternatively to 28 deg "pie slices" in order to block for any differences in soil types underneath the pivot. The two radial and three arc-wise replications created a total of six replicate plots for each treatment. A neutron probe access tube was located in the center of each plot (48 total tubes) in the crop row (top of the bed). Two additional rows of soybeans were planted around the outside and inside edges of the pivot to help minimize border effects. Agronomic practices common in the region for high yields were applied.

The pivot's position was determined using a low-cost GPS receiver mounted near the end of the pivot (Peters and Evett 2005). The pivot movement and positioning were controlled remotely by a computer, located in a nearby building, which communicated through two different 900 MHz radios (Fig. 3). One radio was part of a center pivot remote control system "base station" produced by Valmont Industries. This radio communicated with the pivot through a second radio mounted at the pivot center point, thus, allowing status checks and control commands to be sent and received at the pivot control panel. The second system consisted of a Campbell Scientific RF400 radio that communicated to similar radios connected to a datalogger mounted on the pivot and a separate datalogger in the field.

The center-pivot-mounted datalogger collected data from 16 infrared thermocouple thermometers (IRTCs) that were attached to the trusses of the pivot (Figs. 3 and 4). They were mounted on the leading side of the pivot trusses (approximately 3 m above the ground surface) and the pivot was only allowed to irrigate in one direction so that the sensors would not view wet canopy. The IRTCs were oriented so that they pointed parallel to the center pivot arm (perpendicular to crop rows) towards a spot in the middle of each concentric irrigation treatment plot. In order to minimize sensor angle related effects, two IRTCs were aimed at approximately the same spot from either side of each plot. The average of these two readings for each plot was used. Wanjura et al. (1995) reported that canopy temperatures differed less than 0.5°C when measured by either one sensor in the nadir position, or two sensors pointed at the row from opposite directions. The IRTCs were connected to a multiplexer (Campbell Scientific AM25T) at the second tower, which in turn was connected to a datalogger placed at the third and last tower. The IRTCs sensed canopy temperature on 10 sec intervals, and the 1 min averages were logged.

In 2004, the IRTCs used were narrow field of view (ratio of distance to view spot size was 10:1) (Exergen model IRt/c.JR-10) and were sensed by a Campbell Scientific CR10X datalogger. At the end of the season in 2004 it was discovered that the narrow field-of-view IRTCs were sensitive to the sensor body temperature, causing temperature errors. Thus, in 2005, a wider field-of-view (2:1) sensor (Exergen model IRt/c.2-T-80), which was relatively insensitive to sensor body temperature, was used and mounted on additional structures built on the pivot so that the sensors could be placed closer to the canopy (approximately 1 m from the ground surface) to avoid seeing wetted canopy.

Sixteen IRTCs (Exergen model IRt/c.2-T-80) were mounted in stationary locations in the field and connected to a separate datalogger (Fig. 3). Each IRTC was mounted in the nadir position over the crop row close enough to the canopy so that soil was not included in the field of view. These IRTCs were adjusted up with the changing height of the canopy. One IRTC was mounted in each irrigation level of both the automatic and manual treatments. These IRTCs were similarly connected through a multiplexer (Campbell Scientific AM25T) and to a datalogger (Campbell Scientific CR21X). The datalogger logged the 5 min averages of each of the IRTC readings collected on 10 sec intervals.

Each IRTC was separately calibrated using a black body (Omega Black Point, model BB701) before the season began. A second order polynomial was fitted to the results of the calibration and each IRTC was individually corrected by the data analysis software running on the control computer in the nearby building. The sensors were checked periodically throughout the season and they seemed relatively unaffected by dust or bugs.

During an automatic irrigation event, the pivot stopped at the edge of the treatment, paused 10 min to drain, and then ran dry over the manual irrigation treatment. It would then pressure up again for the next automatic irrigation treatment, and continued on in this fashion until all of the automatic irrigation segments were irrigated. An application depth of 20 mm was applied at each automatic irrigation event. This was equivalent to the maximum, two-day evapotranspiration rate for the region during the hot, windy summer months. After irrigating the last automatic plot, the pivot continued on around dry to its starting point. During a manual irrigation event, the pivot performed similarly except it would irrigate only the manual irrigation treatments at a manually set application depth required to replenish soil water content to field capacity ($0.33\ \mathrm{m^3\ m^{-3}}$), thus, preventing crop stress for the 100% treatments. The soil water deficit was determined by weekly neutron probe readings in the 100% manual irrigation treatments. The neutron probe was field calibrated as in Evett and Steiner (1995) and was read at 20 cm depth increments. A depth control stand (Evett et al. 2003) was used to improve accuracy in the near-surface (10 cm depth) reading. In order to both manually and automatically control the same pivot, automatic irrigations were only allowed on even days of year, and manual irrigations were only allowed on odd days of year.

The central control computer was programmed to call the pivot-mounted datalogger and the pivot control panel every minute to retrieve status reports. Software was written in Visual Basic that reviewed the status reports every minute to determine whether the pivot had crossed a plot boundary. If it had, new instructions were sent to the pivot depending on its location and the program (automatic or manual) that was running at the time. In this way, the complex motion of the center pivot was controlled.

The field datalogger was polled only once a day soon after midnight. At this time, the previous day's data were analyzed to determine the next day's strategy. If the pivot did not move during the previous day, the temperature curve collected by the pivot-mounted IRTCs was used to determine whether irrigation was required based on the canopy temperature measurements from where the pivot was located. If the pivot *did* move during the previous day, then a subroutine was called that scaled one-time-of-day temperature measurements and made decisions based on the results. The two canopy temperature measurements from the field-mounted IRTCs in the 100%, automatic treatments were averaged together and used as the reference curve for scaling the one-time-of-day measurement into a diurnal curve [Eq. (1)].

To establish the plots, the plots were uniformly irrigated until the soil between the rows was not visible when viewed at a 45 deg angle from the pivot IRTCs. At the end of the season, the dry yield was determined by harvesting a $3.48\ \mathrm{m^2}$ sample near the center of each plot. The total dry biomass was measured, as well as the dry yield Y ($\mathrm{kg\ m^{-2}}$), and average bean weight. The total water use W_U (m) was determined by subtracting the soil profile water content (m) determined at the first measurement date from the water content determined after harvest, and adding the total amount of irrigation I (m) and rainfall (m) for that time period. Water use efficiency (WUE) was calculated as

$$\mathrm{WUE} = \frac{Y}{W_U} \tag{2}$$

and irrigation water use efficiency (IWUE) was calculated as

$$\mathrm{IWUE} = \frac{Y - Y_D}{I} \tag{3}$$

where Y_D=mean yield ($\mathrm{kg\ m^{-2}}$) in the dryland plots. Both WUE and IWUE are given in units of $\mathrm{kg/m^3}$.

Results and Discussion

Exergen IRTCs have a capacitor built into the sensor to help to minimize the effects of ambient electromagnetic noise on the sensor's readings. This capacitance interacts with the Campbell Scientific CR10X datalogger to give readings that are slightly incorrect. The pivot IRTCs were wired into a CR10X. This is not an issue with the Campbell Scientific CR21X, which was used for the stationary field measurements. The readings from the narrow field-of-view sensors that were mounted on the pivot also were very sensitive to the sensor body temperature. These errors were much higher than those from the wider field-of-view sensors mounted in the field. It was learned that these were simply poor sensors that were subsequently replaced by the manufacturer for virtually no cost. Because the sensors were calibrated independently in the laboratory before mounting them on the pivot, and because the readings were reasonable, this error was not caught until after the 2004 season was effectively over. This resulted in pivot IRTC temperatures that were 3–5°C low.

The pivot IRTC measured temperatures were compared to the field IRTC data from times when the pivot was located in approximately the same location. The temperatures from the pivot mounted IRTC temperatures varied linearly with the more correct field IRTCs. Regression was used to obtain the equation

$$T_{\mathrm{corrected}} = 0.7641 \times T_{\mathrm{pivot}} + 9.1713 \tag{4}$$

This equation was used to obtain a corrected ($T_{\mathrm{corrected}}$, °C) canopy temperature using the observed IRTC pivot temperatures (T_{pivot}, °C), (r^2 of 0.9731).

To evaluate the effect that this error had on the irrigation experiment, the corrected temperatures were processed with a specifically written computer program. The irrigation decisions (of what should have happened) were compared against what was actually done. The results showed that in five different instances throughout the season, automatic irrigations should have run, but did not because the temperatures were reported low. The temperature threshold was effectively set at 30°C instead of the 27°C for soybeans that is specified by theory. When tested, there was no difference in the irrigation decisions made by the uncorrected data with a 30°C temperature threshold and the corrected temperatures with a 27°C temperature threshold. A different IRTC was used in 2005 as described above and the problem was corrected for the following season. The yield and water use data were analyzed using SAS (SAS Institute, Inc., Cary, N.C.) with a procedure for mixed models (proc mixed) with the Tukey-Kramer method for adjusting for multiplicity. Results are given in Tables 1 and 2.

In 2004, the manual irrigation treatment yielded significantly more than the automatic irrigation treatment ($\mathrm{Pr} > |t| = 0.035$) with an average difference of $0.025\ \mathrm{kg/m^2}$ (Table 1). We believe that this was mainly due to the sensor issue, which was equivalent to the temperature threshold being set 3°C greater than it should have been. Although not significantly different, the manual treatments also showed numerically larger WUE and IWUE. For this first season, there were no significant differences between the automatic and the manual treatments for any variable (yield, bean mass, etc.) within an irrigation level, with the exception of yield at the 67% irrigation level.

The automatic treatment yielded better in 2005 with the IRTC issue corrected than the manual irrigation treatment (Table 2). The differences in the treatments could be seen in the crop heights. This difference as measured in yield was not significant, however. Because the described system can sample the water stress of an entire field instead of discrete points and because the automatic system makes irrigation management easier, a nonsignificant difference is viewed as a win. In fact, yields from the manual and automatic treatments were not significantly different from each other at any of the irrigation levels. The automatic treatment used

Table 1. 2004 Response Variables for the Treatment (Automatic versus Manual), the Irrigation Level (100, 66, 33%, and Dry), and the Cross between the Two. Numbers in a Column Followed by the Same Letter Are Not Significantly Different at the 0.05 Probability Level.

Treatment	Dry yield (kg/m^2)	Average bean weight (mg/bean)	Biomass (g)	Water use efficiency (kg/m^3)	Irrigation water use efficiency (kg/m^3)	Total water use (mm)
Manual	0.295 A	185 A	2195 A	0.627 A	0.961 A	455 A
Automatic	0.0270 B	187 A	2008 B	0.603 A	0.909 A	435 B
Irrigation level (%)						
100%	0.400 A	307 A	2961 A	0.667 A	0.783 C	600 A
67%	0.345 B	159 B	2452 B	0.686 A	0.925 B	502 B
33%	0.256 C	152 B	1860 C	0.652 A	1.097 A	392 C
Dry	0.130 D	127 B	1134 D	0.456 B		285 D
Treatment irrigation level						
Manual 100%	0.411 A	303 A	3096 A	0.663 AB	0.757 C	620 A
Automatic 100%	0.389 A	311 A	2825 AB	0.671 AB	0.809 C	580 B
Manual 67%	0.374 A	157 B	2596 BC	0.722 A	0.978 ABC	517 C
Automatic 67%	0.317 B	160 B	2308 C	0.651 AB	0.873 BC	488 D
Manual 33%	0.271 C	152 B	1942 D	0.683 AB	1.149 A	396 E
Automatic 33%	0.240 C	151 B	1779 D	0.621 B	1.045 AB	387 E
Manual dry	0.125 D	128 B	1147 E	0.441 C		285 F
Automatic dry	0.134 D	127 B	1121 E	0.471 C		285 F

more water than the manual treatment and resulted in slightly smaller, though not significantly different, water and irrigation water use efficiencies.

Yields at the 100% irrigation level were in the range reported by Evett et al. (2000) for three years of automatically drip irrigated soybean, and by Eck et al. (1987) for three years of fully furrow irrigated soybean. Water use efficiencies were larger than those reported by Evett et al. (2000), which ranged from 0.25 to 0.51 kg m^{-3} for drip irrigated soybean at the same location. They were also larger than values ranging from 0.05 to 0.61 kg m^{-3} reported by Eck et al. (1987). Contrary to results of Evett et al. (2000) and Eck et al. (1987), water use efficiency in 2005 was increased by deficit irrigation, though not in 2004. WUE was much higher in 2005 because the total water use was much lower due to lower evapotranspirative demand. The overall average total water use (WU) in 2005 was 236 mm. In 2004, it was almost twice that at 445 mm. In 2005, there was only 27 mm of precipitation and an average of 133 mm of irrigation across all of

Table 2. 2005 Response Variables for the Treatment (Automatic versus Manual), the Irrigation Level (100, 66, 33%, and Dry for Both Automatic and Manual), and the Cross between the Two. Numbers in a Column Followed by the Same Letter Are Not Significantly Different at the 0.05 Probability Level.

Treatment	Dry yield (kg/m^2)	Average bean weight (mg/bean)	Biomass (g)	Water use efficiency (kg/m^3)	Irrigation water use efficiency (kg/m^3)	Total water use (mm)
Manual	0.272 A	133 A	1222 A	1.30 A	0.77 A	218 B
Automatic	0.289 A	130 A	1306 A	1.18 A	0.73 A	254 A
Irrigation level (%)						
100%	0.383 A	148 A	1630 A	1.10 A	0.77 A	351 A
67%	0.321 B	140 A	1380 B	1.18 A	0.80 A	273 B
33%	0.239 C	125 B	1112 C	1.25 A	0.69 A	193 C
Dry	0.178 D	114 B	934 D	1.43 A		127 D
Treatment irrigation level						
Manual 100%	0.374 A	150 A	1556 AB	0.16 B	0.84 A	323 B
Automatic 100%	0.391 A	145 A	1705 A	1.03 B	0.71 A	379 A
Manual 67%	0.307 B	143 A	1310 CD	1.21 B	0.82 A	254 C
Automatic 67%	0.335 B	138 AB	1451 BC	1.15 B	0.78 A	282 B
Manual 33%	0.229 C	126 BC	1064 EF	1.28 AB	0.66 A	180 D
Automatic 33%	0.249 C	124 CD	1159 DE	1.21 AB	0.72 A	207 D
Manual dry	0.177 D	113 D	958 F	1.54 A		116 E
Automatic dry	0.180 D	114 CD	909 F	1.33 AB		137 E

the plots. In 2004, there was 211 mm of precipitation and 173 mm average irrigation across all of the plots. The large differences in the dry (no irrigation) treatment yields and total water use between years demonstrates the large difference in precipitation between the two years.

Summary and Conclusions

A center pivot was configured to automatically irrigate, based on crop stress signals sensed by infrared thermocouples mounted on the center pivot. These automatic treatments were compared with a manually scheduled treatment over two growing seasons in 2004 and 2005. In 2004, there was an interaction of the sensors with the datalogger, and incorrect canopy temperatures were recorded by the pivot-mounted IRTCs. This resulted in the equivalent of the threshold temperature being set at 30°C instead of the prescribed 27°C. Therefore, the automatic irrigations ran less often than they should have in 2004. Because of this, the manual treatments yielded significantly more than the automatic treatments. However, during the following season, the difference between the manual and automatic irrigation treatments was not significant, with the automatic treatment yielding slightly more than the manual treatment. There were no significant differences in water use efficiency in either year. By helping with irrigation scheduling on center pivots, the automatic irrigation system saves management time and lessens decision making, and a nonsignificant difference is viewed as a win. We believe that the costs and simplicity of methods presented here may become attractive to producers when available in a turnkey commercial package. This is especially true since the methods have the potential to simplify management and reduce labor costs, while maintaining or increasing yields compared with intensively and scientifically managed manual irrigation scheduling.

Acknowledgments

Mention of trade names or commercial products in this paper is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Notation

The following symbols are used in this paper:

I = total amount of irrigation;
IWUE = irrigation water use efficiency;
$T_{\text{corrected}}$ = corrected canopy temperature;
T_e = predawn canopy temperatures throughout the field;
T_{ref} = canopy temperature from the reference location at the same time interval as T_{rmt};
$T_{\text{ref},t}$ = measured reference temperature from the time t that the remote temperature measurement was taken;
T_{rmt} = calculated canopy temperature at the remote location;
$T_{\text{rmt},t}$ = one-time-of-day canopy temperature measurement at the remote location at any daylight time t;
T_{pivot} = pivot temperatures;
W_U = total water use;
WUE = water use efficiency;
Y = dry yield; and
Y_D = mean yield.

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